KECK INTERFEROMETER

The Keck Interferometer

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Jet Propulsion Laboratory, California Institute of Technology

OCA, July 13, 2001

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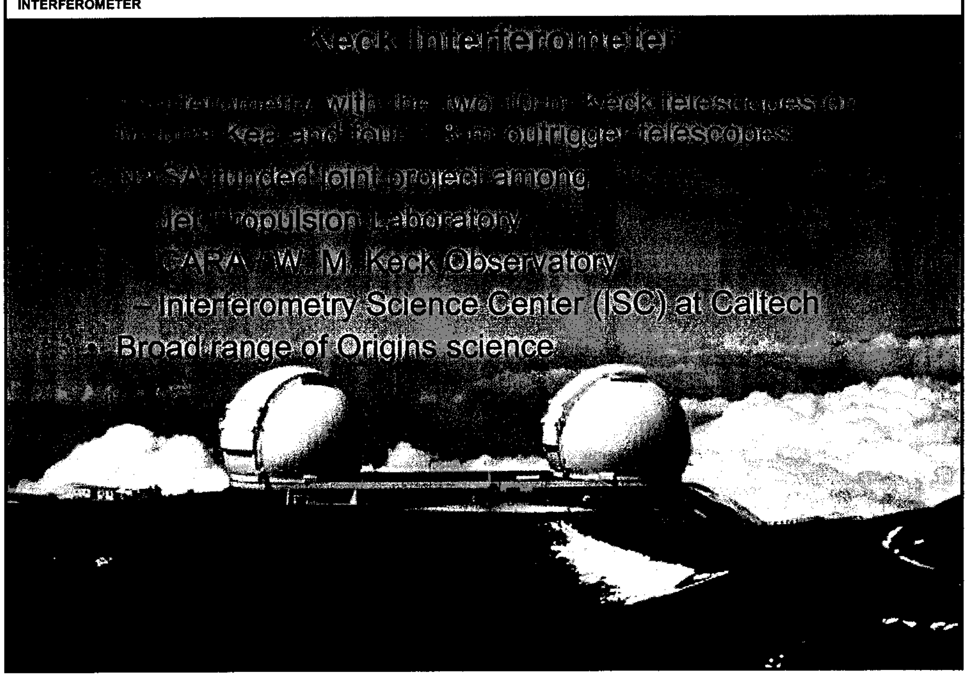

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Outline

- The NASA Origins Program
- What's an interferometer?
- Elements of an interferometer
- Keck Interferometer science applications
- First Keck Interferometer fringes and current status

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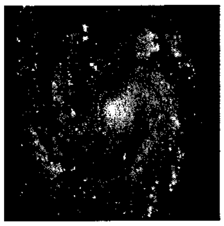
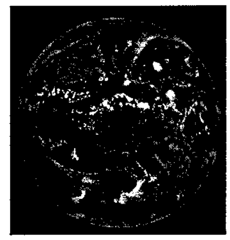
The NASA Origins Program

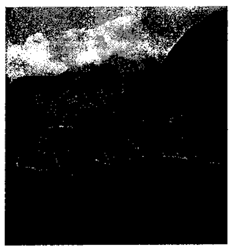
NASA's Astronomical Search for Origins



To understand how galaxies formed in the early universe and to determine the role of galaxies in the appearance of stars, planetary systems and life.

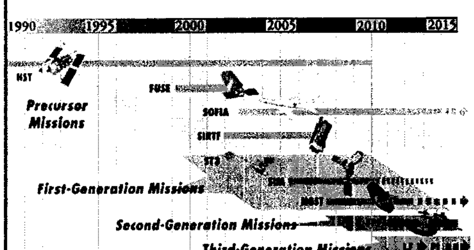


To understand how stars and planetary systems form and to determine whether life-sustaining planets exist around other stars.



To understand how life originated on Earth and to determine if it began and may still exist elsewhere as well.

Origins Space-Based Observatories



- Precursor Missions
  - **HST** (Hubble Space Telescope) 4/90
  - **FUSE** (Far Ultraviolet Spectroscopic Explorer) - 6/99
  - **SOPHIA** (Stratospheric Observatory for Far Infrared Astronomy) - 2002
  - **SIRTF** (Space Infrared Telescope Facility) 12/01
- First Generation Missions
  - **ST3** (Space Technology 3)
  - **SIM** (Space Interferometry Mission)
  - **NGST** (Next Generation Space Telescope)
- Second Generation Mission
  - **TPF** (Terrestrial Planet Finder)

Origins Ground-Based Observatories

- Keck Observatory: Using 1/6 of Keck's observing time, NASA focuses the "eyes" of the world's largest twin telescopes on incredible galactic and stellar phenomena.
- Keck Interferometer: By connecting the twin Keck telescopes and combining incoming light, Keck will function as a single, much larger and more powerful telescope.
- Palomar Testbed Interferometer: By combining light from telescopes at the Palomar Observatory, PTI takes the first crack at developing technologies that combine light coming in from distant objects in the cosmos

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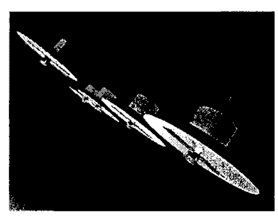
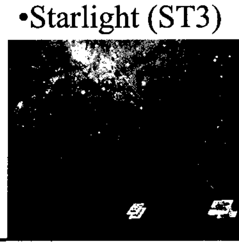
Interferometry plays a key role in the Origins Program

•Space Interferometry Mission (SIM)

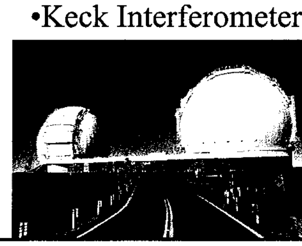


•Terrestrial Planet Finder (TPF)

•Starlight (ST3)



•Keck Interferometer



What's an interferometer?

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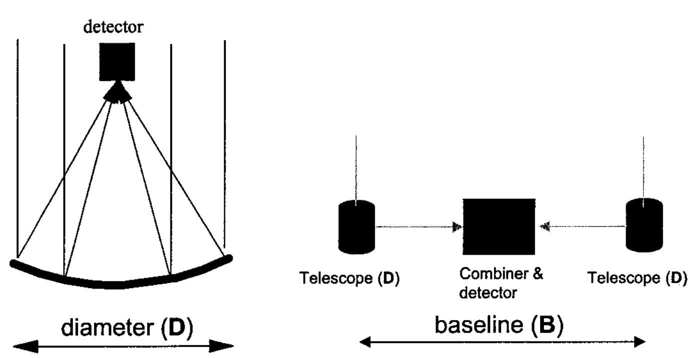
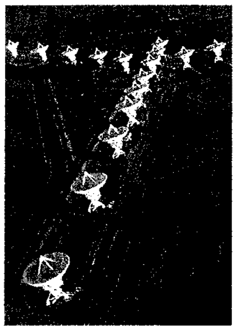
What is an interferometer?

- An interferometer combines the light from several small telescopes to yield the angular resolution of a much larger telescope

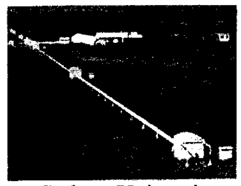
Telescope **Interferometer**



Radio/Optical Interferometers

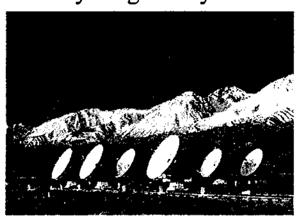


Very Large Array

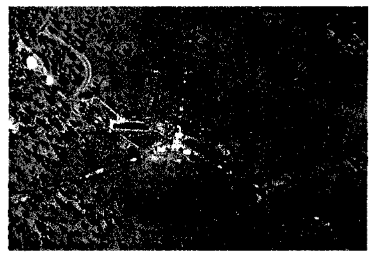


Sydney University

Palomar Testbed Interferometer



Caltech MM Array



Navy Prototype Optical Interferometer

Why Build Interferometers?

- Imaging resolution
  - Resolution can be (cost effectively) improved by increasing the separation of the apertures
- Astrometric accuracy
  - Interferometers have a simple geometry which can be monitored to achieve high accuracy
- High dynamic range capability
  - Interferometers have the ability to “null starlight” to detect faint objects near a bright star

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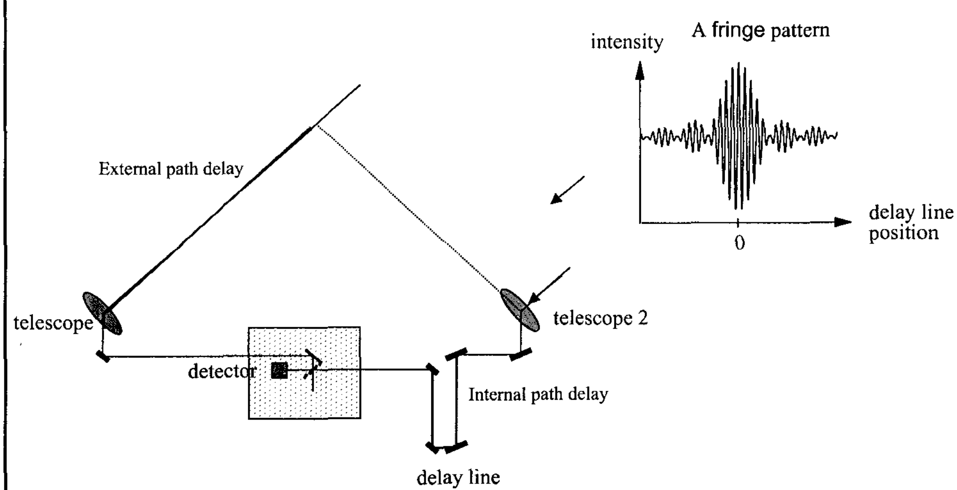
How does a stellar interferometer work?



The delay line moves to delay the light from telescope 2 so that the light from both telescopes arrives at the detector at the same time

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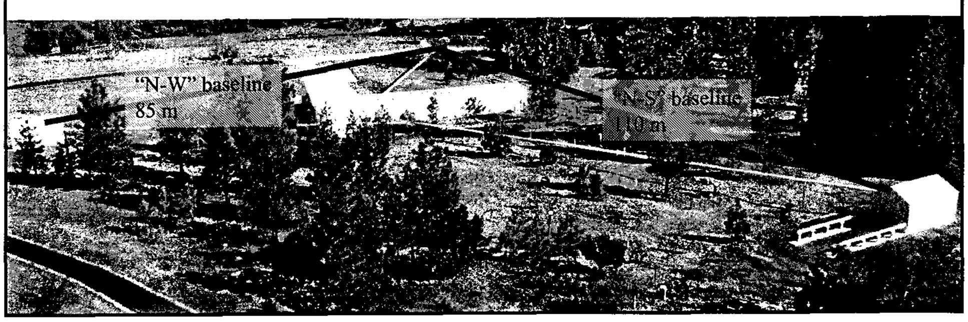
Interferometer Testbeds

Palomar Testbed Interferometer

- 2-way system, 110 m max baseline
- 40 cm collecting apertures
- Active broadband fringe tracking at K (2-2.4 μm) or H (1.5-1.8 μm)
- Spectrometer resolution of R = 25 – 50
- Angle tracking at R + I (0.7 – 1.0 μm)
- Dual-star capability for narrow-angle astrometry

More detail:
ApJ 510, 505 (1999)



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Elements of an Interferometer

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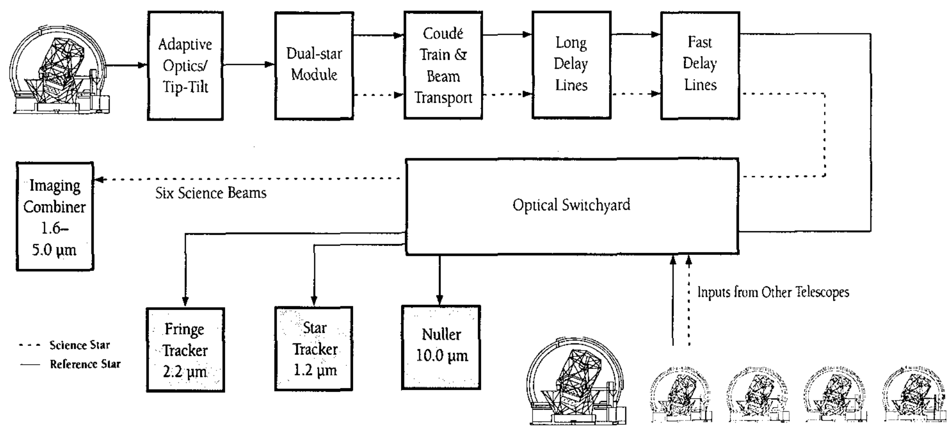
Keck Interferometer Fact Sheet

- Michelson interferometer
  - Two 10-m Keck telescopes, 85 m baseline
  - Four 1.8-m outrigger telescopes, 30-135 m baselines
- Adaptive optics (natural guide star) on both 10 m telescopes
- Infrared fringe detection and tracking
- Instrumentation
  - Two-way beam combiners at 1.5 - 2.4 mm
  - Nulling combiner at 10 mm
  - Multi-way imaging combiner at 1.6 - 5 mm

Keck Interferometer Beam Train



The Summit of Mauna Kea

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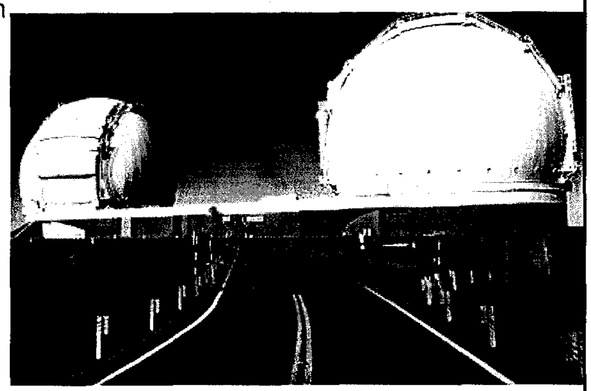
Keck Telescopes

- The twin Keck telescopes on the summit of Mauna Kea on the Big Island of Hawaii
  - The world's largest optical and infrared telescopes
  - Primary mirrors:
    10 m diameter
    36 hex. segments
  - Keck I: 1993
    Keck II:1996
  - Operated by Caltech, Univ. of Calif, and NASA



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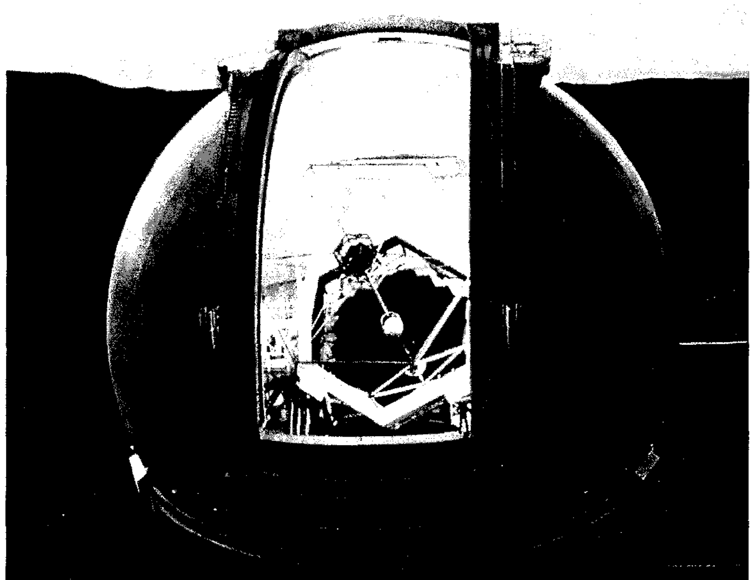
Inside the Dome



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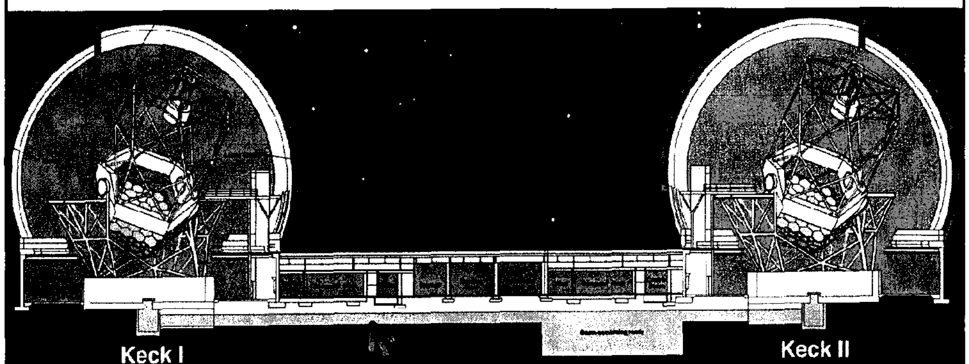
Side view of Keck 1 and 2



Coude tunnel

Interferometer basement

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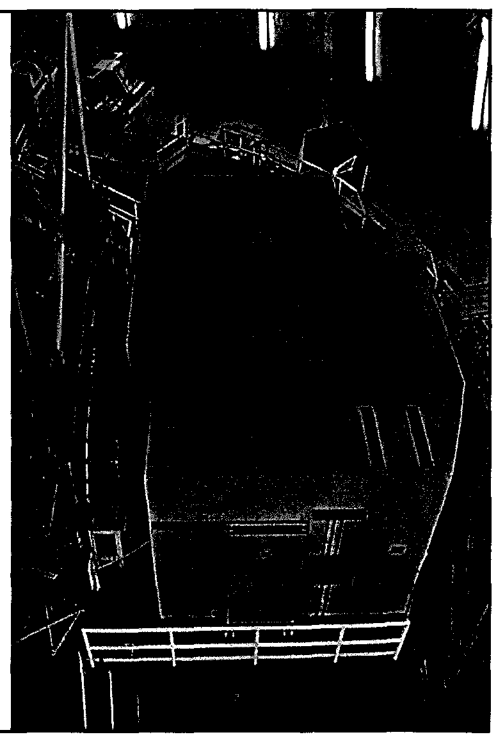
Adaptive Optics

- Each telescope has an adaptive optics (AO) system
  - K2: W.M. Keck Foundation
  - K1: Added for the interferometer
- Corrects images blurred by atmospheric turbulence
  - Provides diffraction-limited images in the near infrared

Keck II Nasmyth Platform Enclosure



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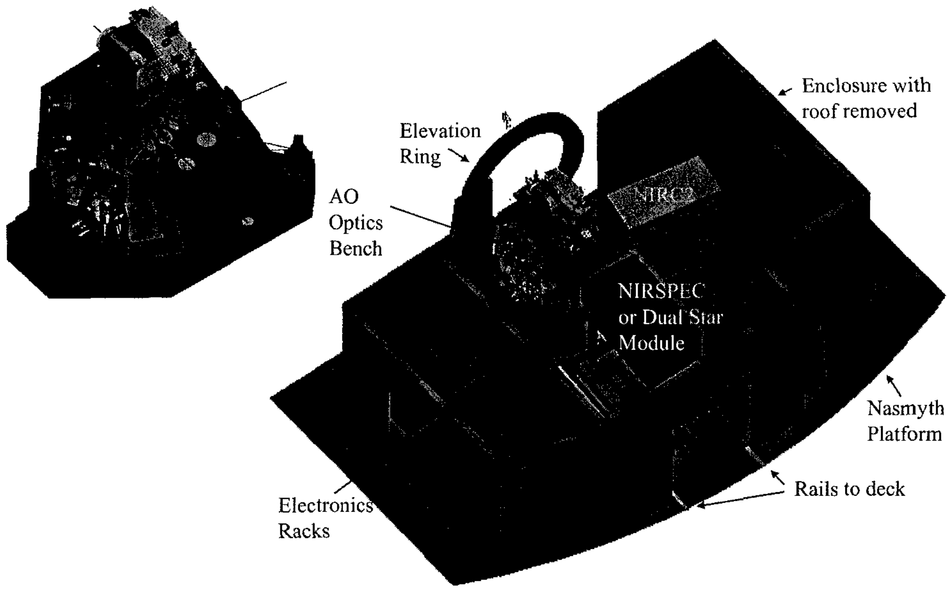
Keck II Left Nasmyth Platform



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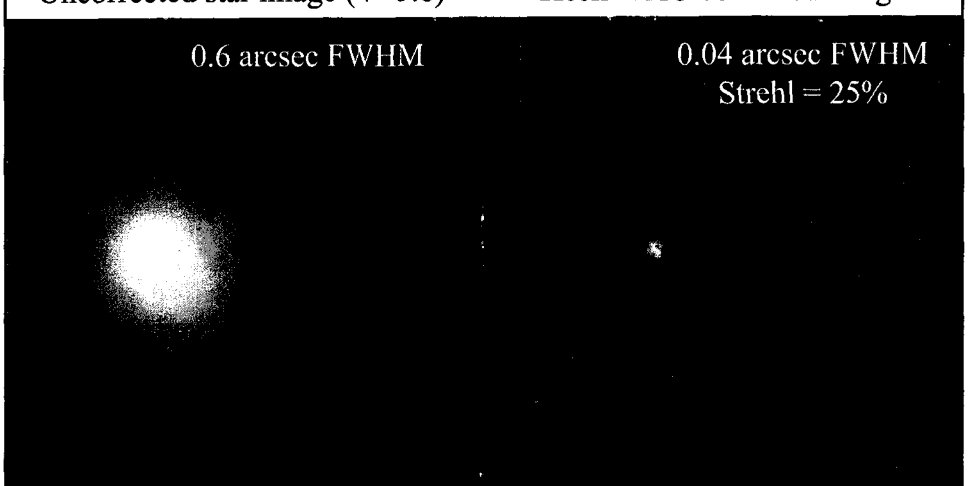
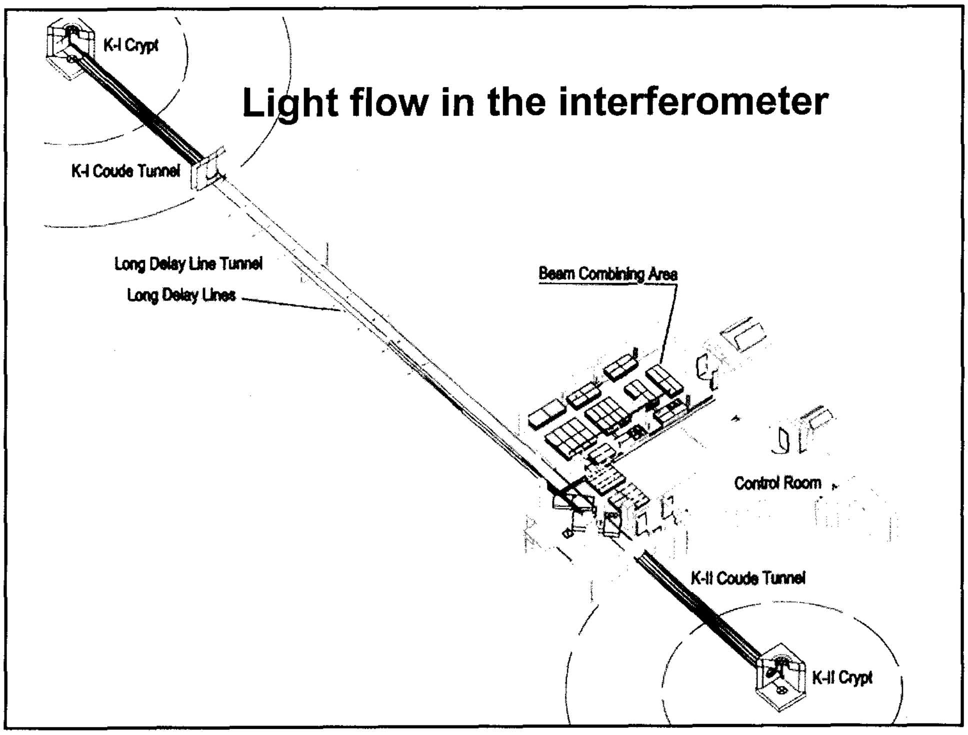
Corrected and Uncorrected Images

Uncorrected star image (V=5.8) Keck II AO corrected image

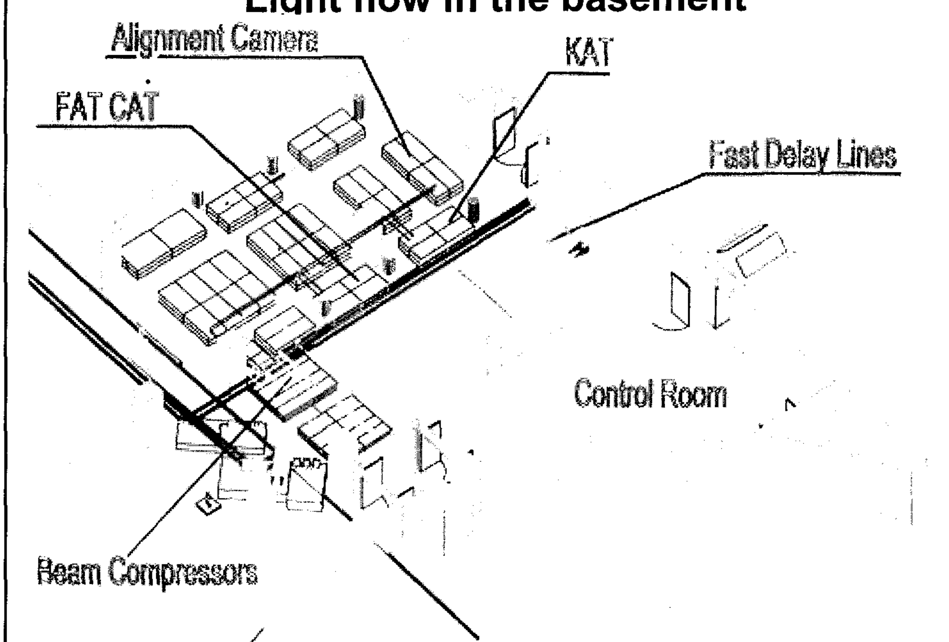


H-band images (autoscaled to peak) - 4.5 arcsec FOV

Light flow in the interferometer



Light flow in the basement



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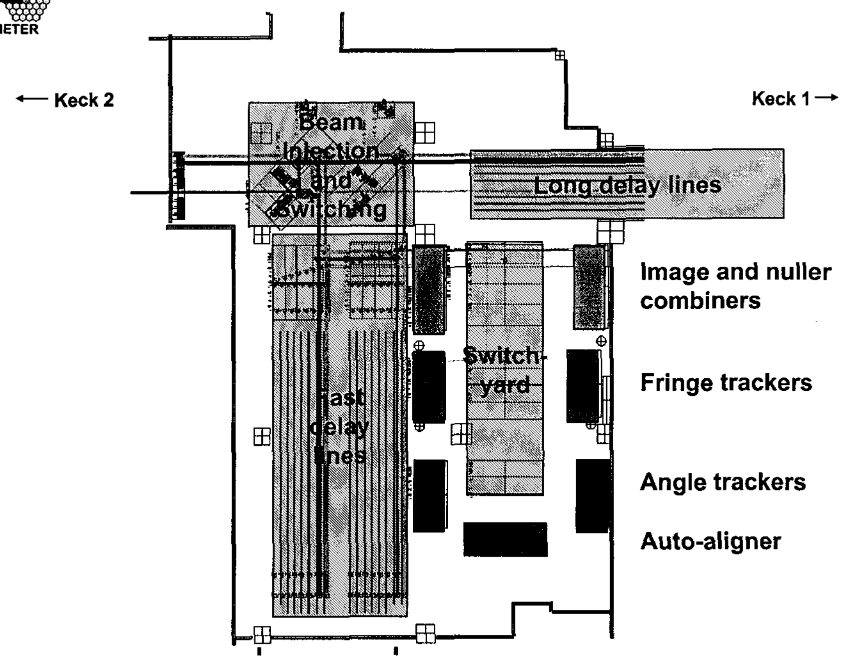
Basement Layout



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Basement - left

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Basement - center

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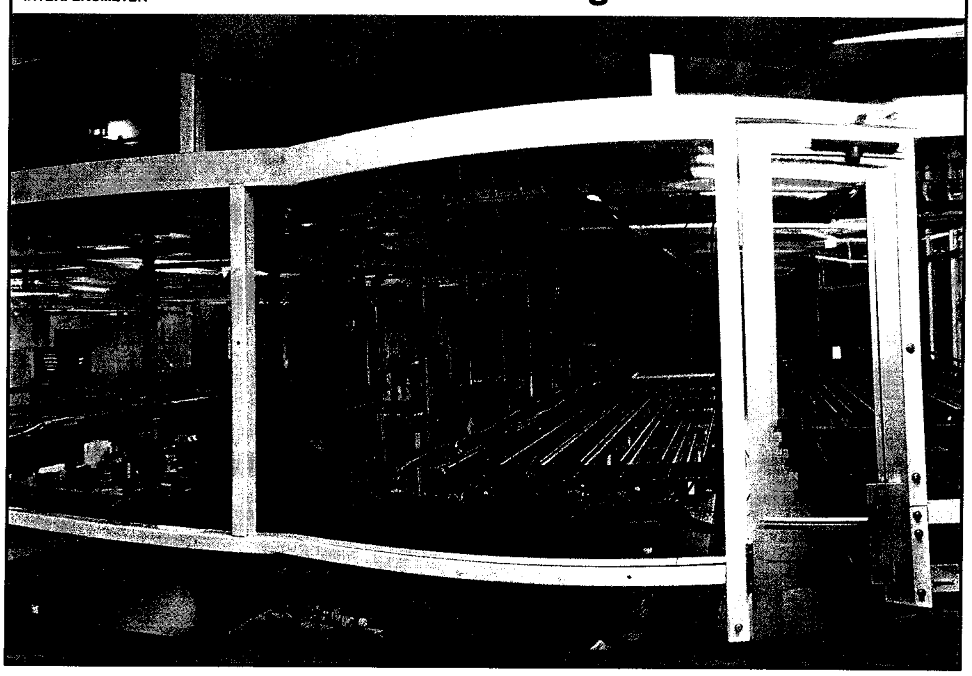
Basement - right



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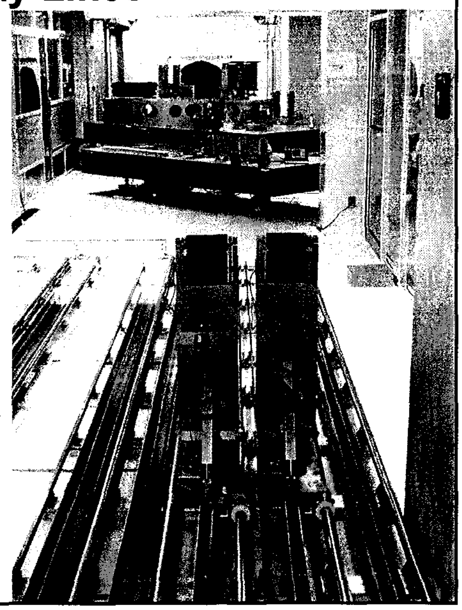
Long Delay Lines

- LDL sleds move along coude tunnel in basement
  - 'Move and clamp' operation to provide delays up to 170 m
  - Stationary during an observation



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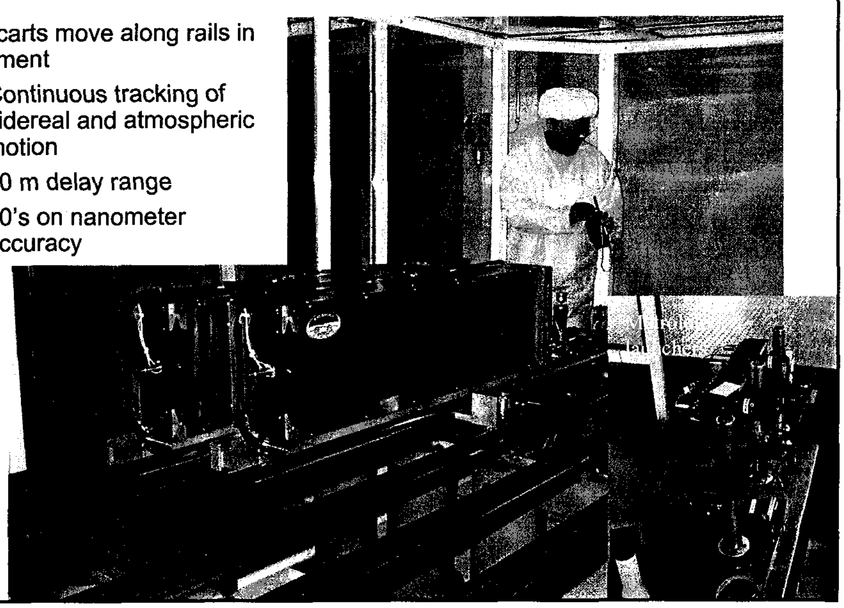
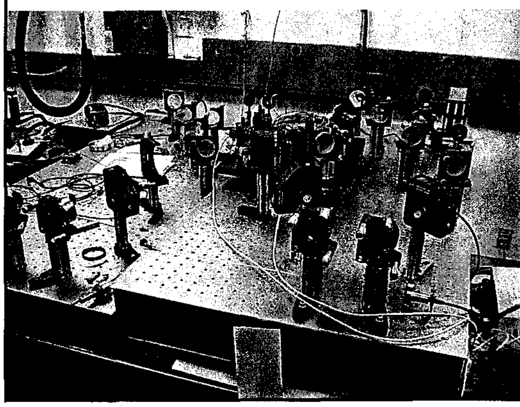
Fast Delay Lines

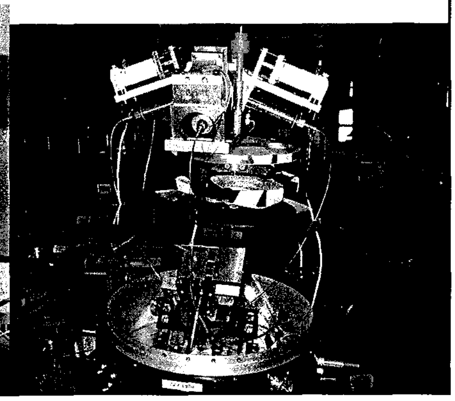
- FDL carts move along rails in basement
  - Continuous tracking of sidereal and atmospheric motion
  - 20 m delay range
  - 10's on nanometer accuracy



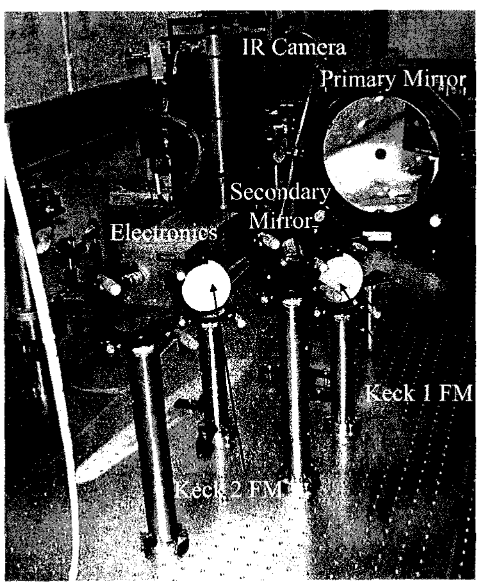
Fringe Detector

- Combines the light from two telescopes
- Detects the interference fringe in the near infrared (H & K)
- Combined light fed into single-mode optical fibers
- Fiber feeds infrared detector in cryogenic dewar





Angle tracker



- Takes light from two or more telescopes
- Keeps the wavefronts from each telescope parallel to each other

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What can you do with all this hardware?

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Science with Keck Interferometer

1 Characterization of exo-zodiacal emission at 10 μm around nearby stars
2 Spectroscopic detection of warm, giant planets
3 Astrometric detection of Uranus-mass planets
4 Imaging of protoplanetary disks, AGN. etc.

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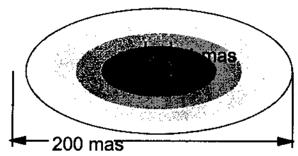
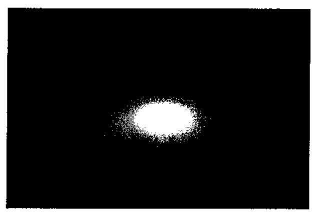
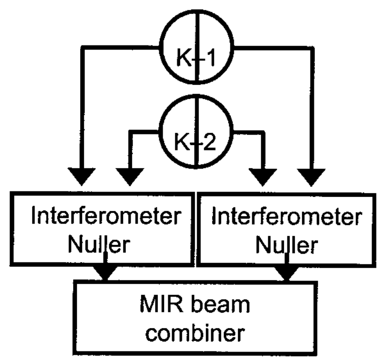
1: Detection of Exo-zodiacal Dust Around Nearby Stars

- Target accuracy: < 10 solar-system equivalents
- Approach: multi-baseline nulling at 10 μm
  - Send two beams to basement from each telescope
  - Null star on each of two K1-K2 baselines
  - Interfere nulled outputs with two-way combiner



1AU radius disk at 10 pc





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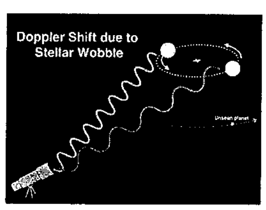
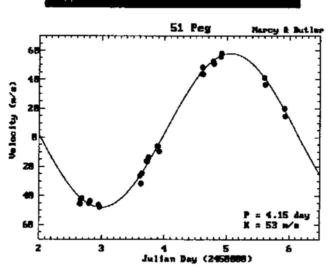
51 Peg, the First Extra-Solar Planet





- Discovered by Michel Mayor and Didier Queloz, Oct 1996, confirmed by G. Marcy and P. Butler
  - Mass > 0.44 Jupiter
  - Period 4.2 days
  - Distance from star 0.051 AU
- Since then the doppler technique has discovered dozens of planets around nearby stars.
- These planets are nothing like the ones in our own solar system

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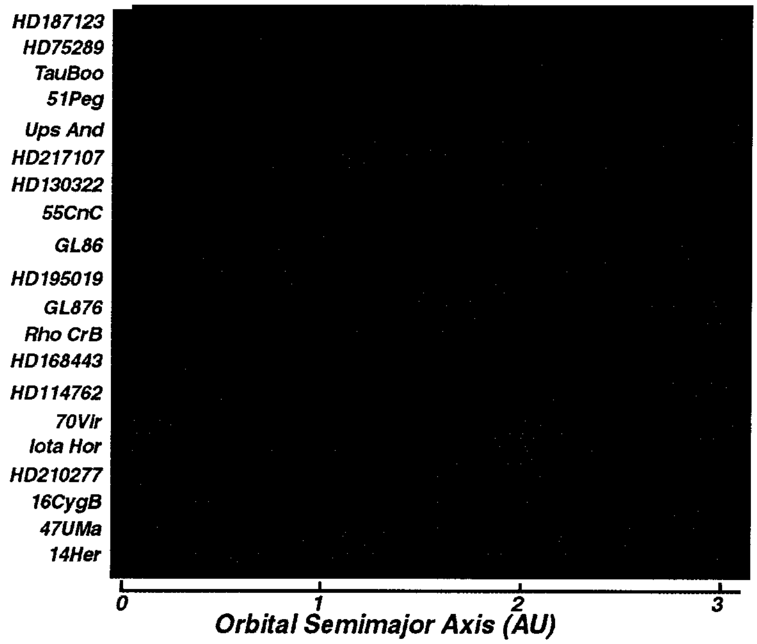
Planet Census from Radial Velocities (Marcy et al.)



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Properties of detected extrasolar planets

- Properties
  - Typical masses like that of Jupiter
  - Many in close (<0.2AU) orbits around the parent star
  - Eccentric orbits (elliptical, not circular orbits)
- What are the properties of planets in our solar system?
  - Jupiter mass Gas Giants far from the Sun (5 - 40 AU)
  - Rocky planets (Earth, Mars, Venus, Mercury) near the Sun
  - Circular, coplanar orbits

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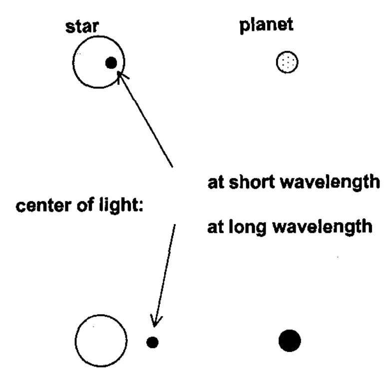
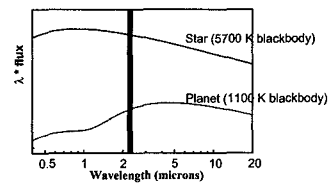
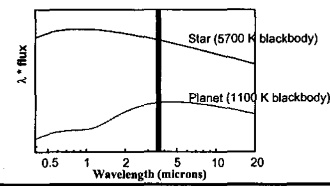
2: Detection of Hot Jupiters

- Use differential phase technique to directly detect extra-solar planets and stellar companions via wavelength dependence of system fringe position
- Target accuracy: 51 Peg signature







(approximation for star-planet separation << fringe spacing)

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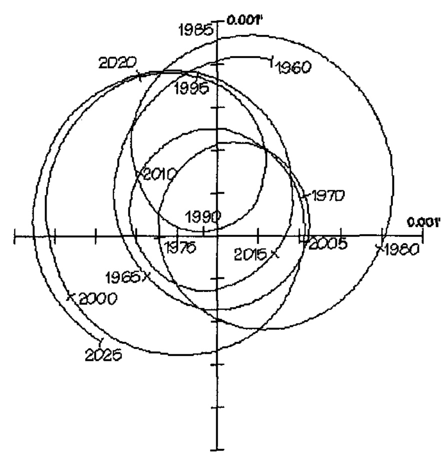
Astrometric Search for Planets

- Astrometry measures positional wobble due to planets
  - Complementary technique to radial velocities
- Jupiter at 10 pc produces 500 uas amplitude - can do from ground
- Earth at 10 pc produces 0.3 μas amplitude - must do from space



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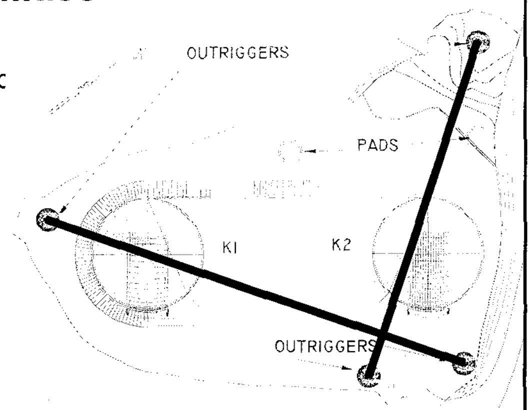
3: Astrometric Search for Planets to Uranus Mass

- Configuration
  - Four 1.8 m outrigger telescop
  - Two 100 m baselines
  - Detection of planets down to Uranus mass



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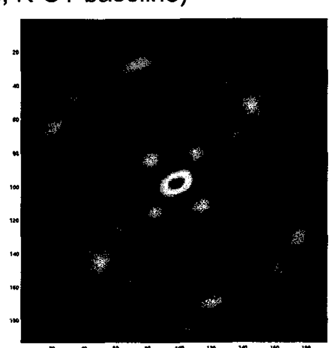
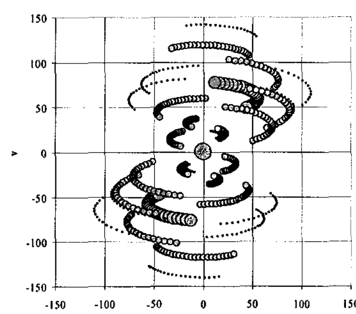
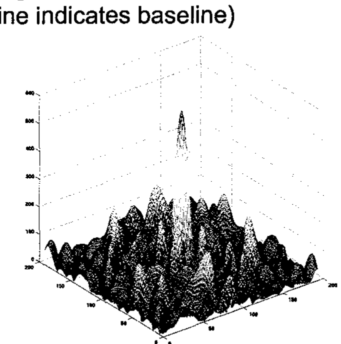
4: Imaging

- Imaging with 6-element array
- 9 of 15 baselines include a 10-m telescope
  - Background-limited sensitivity equivalent to two 4.4-m's
- 2-5 μm imaging detector
- Sensitivity: K=19 (point source, 1000 s, K-OT baseline)





u,v coverage with outriggers and Kecks (width of line indicates baseline)



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Status

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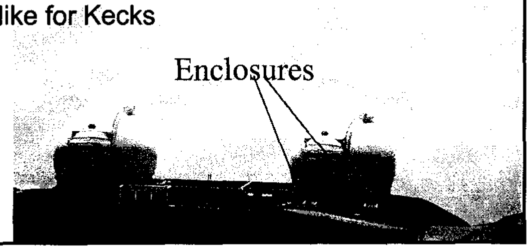
First Siderostat Fringes

- Initial fringes using the siderostats were obtained on Feb. 22, 2001
  - Checked out hardware to be used with Kecks on next run
- Instrument configuration
  - Two 50-cm siderostats feeding fixed 40 cm telescopes (essentially the same as the PTI front-end optics)
  - Angle tracking at H band controlling fast steering mirrors behind telescopes
  - 10 cm compressed beam routed to beam combining lab
  - Remaining configuration like for Kecks



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First Keck-Keck Fringes

- March engineering run: 3 1/2-nights on the two Kecks March 12-14, 2001
- Instrument configuration
  - Two 10 m Kecks feeding interferometer via coude optics
  - Natural guide star adaptive optics running on both telescopes using R and I light
  - Slow guiding corrections from interferometer angle tracker at H band to AO system
  - Fringe detection at K band using interferometer fringe camera
    - » Synchronous demodulation (a.k.a. fringe scanning) at 1 kHz frame rate
    - » Single broadband K channel
  - Laser controlled fast delay lines

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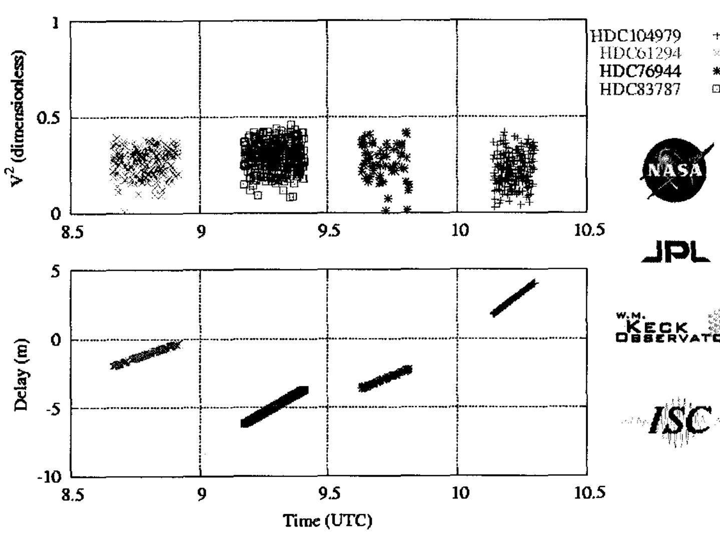
First fringes, March 12, 2001



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At the summit

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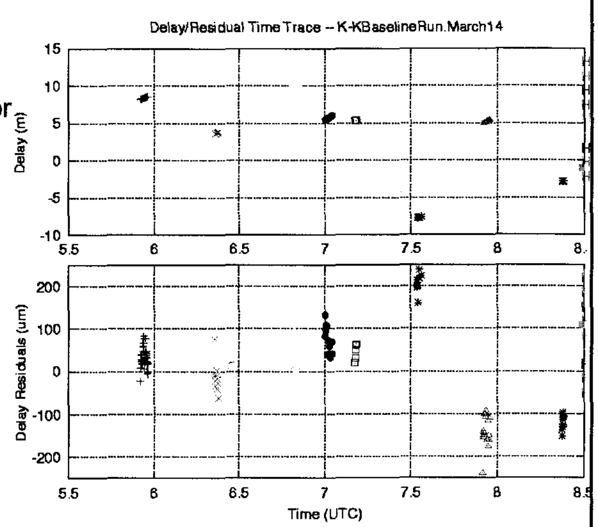
Keck-Keck Baseline Stability

- Test on March 14
- 9 stars used to solve for Keck-Keck baseline using a priori star positions
- Delay range: +/- 10m (fixed LDL) position
- Delay residuals after solution
  - ~100 μm rms using ideal pivot model



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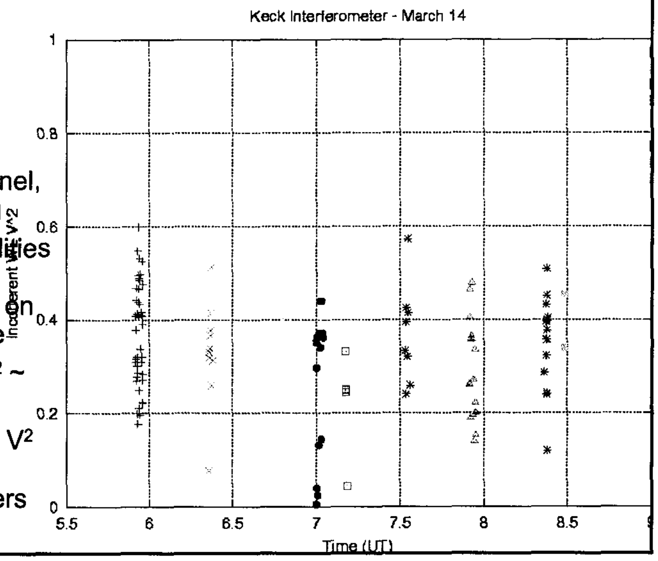
System Visibility

- Test on March 14
- Integrated with baseline tests
- Test used a single broadband K channel, no fringe centering
  - Range of visibilities correspond to different points on fringe envelope
- Peak measured V^2 ~ 55%
  - Implies system V^2 of ~75% given source diameters



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Near terms plans

- Preparation for routine V^2 observations
  - Performance improvements
  - Upgraded fringe camera to provide broadband + spectral channels
  - System characterization (V^2 stability, etc.)
  - More automation and sequencing
- Preparations for nulling and differential phase
- Begin shared-risk science observing

The End

- Interesting web sites
  - http://huey.jpl.nasa.gov/keck
  - http://www2.keck.hawaii.edu:3636
  - http://origins.jpl.nasa.gov

KECK INTERFEROMETER

Finding Planets Indirectly

- Gravitational Effects on Parent Star
  - Radial Velocity Changes
    - » Favors large planets in close to star
    - » Independent of distance
  - Positional Wobble (Astrometry)
    - » Favors large planets far from star
    - » Angular displacement decreases with distance
- Effect of Planet on Star's Brightness
  - Transits of edge-on systems
    - » Small fraction of a percent for a few hours (10^{-5} for an Earth)
  - Gravitational Lensing
    - » Planetary companion of lensing star affects magnification of background star by few percent for a few hours